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Two sides of gender: ERP evidence for the presence of two routes during gender agreement processing

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ABSTRACT

The present ERP study aimed at providing evidence for the existence of two routes in the brain for the processing of morphosyntactic features during language comprehension; a lexical route which retrieves grammatical properties stored in the lexicon without reliance on formal cues, and a form-based route that takes advantage of sub-lexical units strongly related to a specific grammatical class. In the experiment, we investigated grammatical gender agreement processing in Spanish article–noun word pairs using a grammaticality judgment task. Article–noun pairs either agreed or did not agree in gender. Noun transparency was manipulated such that the ending could be strongly associated with a specific gender class (i.e., transparent nouns) or not (i.e., opaque nouns). A visual half-field method was employed and ERPs were recorded in response to the target nouns in order to disentangle the initial hemisphere-specific computations of gender processing. ERP results showed that, while both hemispheres compute agreement dependencies, the left hemisphere is sensitive to the presence of formal gender cues at an early stage (i.e., 350–500 ms) indicating the presence of a form-based route. The right hemisphere showed an ERP effect of transparency, but later than the left hemisphere (i.e., 500–750 ms). These findings confirm the presence of two routes to gender, which can be differently used depending on the availability of transparent endings. In addition, the results showed hemispheric differences in the time course of the form-based route.

1. Introduction

Grammatical agreement is widely used to create long or short distance relations between different elements within a sentence. In the Spanish sentence *el coche es rojo* ("the$_m$ car$_m$ is red$_m$"), for example, the article *el* and the adjective *rojo* establish agreement dependencies with the noun they refer to. A number of studies on this topic have provided evidence that this systematic covariance of grammatical features between different sentence elements plays a crucial role in sentence comprehension (see review in Molinaro, Barber, & Carreiras, 2011). However, how the linguistic system determines the gender of a given noun remains poorly understood. Here, we examined the possibility that a noun's grammatical gender is derived on the basis of two distinct routes: a route based on the noun's lexical features and a route that derives the noun's gender feature from its formal properties. Specifically, the present ERP study investigated the initial, hemisphere-specific computations of gender agreement using the visual-half field (VHF) method, in order to provide evidence for the presence of two different routes for gender processing.

Gollan and Frost (2001) described a model of language comprehension where grammatical gender information can be accessed through a lexical and a form-based route. These two routes can be used whenever the system needs to retrieve the grammatical gender of a given noun (e.g., during the computation of gender agreement dependencies, during a gender decision task). The lexical route derives gender as a lexical feature which is abstractly represented in the mental lexicon. In the case of the preceding example *el coche es rojo*, the system has to recover the gender information of different sentence constituents in order to identify the agreement dependencies. According to the two-route hypothesis, the masculine gender of the noun *coche* can be lexically recovered as an abstract feature stored in the lexicon. The two-route model also predicts that the availability of formal cues to gender (e.g., gender-related noun endings) allows the use of an additional route. For example, in the Spanish sentence *la mesa es roja* (the$_f$ table$_f$ is red$_f$) the noun *mesa* shows the ending –*a*, which is typically associated to feminine gender in Spanish. According to the form-based route, this gender-related ending

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represents an important cue for gender retrieval and the system would take advantage of this distributional information. Hence, the presence of two routes implies processing differences between nouns whose ending is strongly related to a specific gender class (i.e., transparent nouns; e.g., *mesa*) and nouns whose ending is uninformative of gender (i.e., opaque nouns; e.g., *coche*). In transparent nouns, there is a substantial agreement between the two routes since the gender information retrieved from the word form is consistent with the abstract representation of grammatical gender. In opaque nouns, only one of the two routes allows the retrieval of gender information: the abstract node provides the correct gender, while no information can be retrieved at the level of word form.

Evidence for the involvement of these two routes in computing gender comes primarily from behavioural studies. Whereas the presence of a lexical route is generally agreed upon, results supporting the use of a formal route are more mixed. Evidence for the involvement of a lexical route in computing gender comes from a theoretical analysis of the grammatical gender system (Delfitto & Zamparelli, 2009) and from neuropsychological studies (Badecker, Miozzo & Zanutti, 1995; Miozzo & Caramazza, 1997; Vigliocco, Antonini, & Garret, 1997). In Spanish, although most nouns end in –*a* for feminine, and –*o* for masculine, there are a number of opaque nouns (e.g., *reloj*, "watch$_M$") whose ending is not clearly associated to a specific gender class (e.g., "-e", "-n", "-l", "-s", "-j", "-r", "-z"). Furthermore, there is a smaller group of irregular Spanish nouns which reverse the typical gender-to-ending correspondence and end in –*o* (*mano*, "hand$_f$") for masculine and –*a* for feminine (*problema*, "problem$_m$"). In these cases, reliable formal cues are absent and the use of the lexical route is mandatory in order to compute gender and process agreement dependencies. In addition, neuropsychological studies have also shown the importance of the lexical route in recovering gender of transparent, opaque, and irregular nouns. For instance, when people cannot access information about word-form (Badecker, Miozzo, and Zanuttini 1995; Miozzo & Caramazza, 1997; Vigliocco, Antonini, and Garrett 1997), grammatical gender can always be lexically recovered. Since the lexical route can always provide the correct gender of a noun without any reliance on available gender-related endings, it can be considered the most reliable way to retrieve gender (Delfitto & Zamperelli, 2009).

Evidence for the involvement of a formal route in deriving the gender properties of a given noun is less clear-cut. The crucial test in order to check the presence of a second form-based route is the comparison between transparent and opaque/irregular nouns. However, differences in the outcomes of these studies seem to depend on the specific task that is used (Bates, Devescovi, Pizzamiglio, D'Amico, & Hernandez, 1995; Bates, Devescovi, Hernandez, & Pizzamiglio, 1996). A number of studies have shown that participants are able to detect formal cues in order to derive the grammatical gender of nouns. Specifically, in Romance languages, it has been observed that when people have to process gender information, they can take advantage of available gender-related endings. Behavioural responses to transparent nouns (e.g., *mesa*) were compared with responses to opaque nouns (e.g., *coche*) when people had to perform a gender decision task (Bates et al. 1996; Exp. 2 and 3; Bates et al. 1995; Exp. 1; Hernandez, Kotz, Hofmann, Valentin, Dapretto, & Bookheimer, 2004; Taft & Meunier 1998), or a gender agreement judgment task (Bates et al., 1996; Gollan & Frost, 2001). The results revealed that participants took less time and made fewer errors with transparent nouns compared to opaque nouns. The advantages of deriving gender for transparent nouns have been interpreted as evidence in favour of the form-based route. In contrast, other behavioural studies that did not use a task based on gender decision showed similar results for transparent nouns and opaque/irregular nouns (Bates et al., 1995; Exp.2; Bates et al., 1996; Exp.1; Padovani & Cacciari, 2003; Exp.1; but see De Martino, Bracco, & Laudanna, 2010).

It is worth noting that the systematic use of formal cues to gender could lead to errors. For instance, word ending does not always represent a reliable cue for gender retrieval and could sometimes be ambiguous or even misleading. In the case of opaque and irregular nouns, the use of the form-based route is useless or even costly. In the case of transparent nouns, the use of this additional route does not seem to be mandatory and it provides information that is redundant with respect to the abstract representation of gender associated with a noun (Vigliocco & Franck, 2001).

In sum, the behavioural measures collected so far are not always consistent with the presence of a form-based route to gender. In the current study, we attempted to resolve this issue by using Event-related potentials (ERP). The issue of the computation of grammatical gender has been investigated in the ERP literature. Specifically, the time course of gender agreement processing has been widely investigated across different languages (Molinaro et al., 2011). However, no ERP study on agreement violations has directly compared transparent and opaque nouns. Most of the ERP studies on Romance languages have only used transparent nouns to investigate gender agreement processing (Barber & Carreiras, 2003; 2005; Barber, Salillas, & Carreiras, 2004; but see Molinaro, Vespignani, & Job, 2008 for a study with only opaque nouns). These studies showed that gender agreement violations within a sentential context evoked an increased negativity between 300 and 500 ms, followed by an increase of posterior positivity after 500 ms (Barber & Carreiras, 2005, Exp.2; Barber et al., 2004; Molinaro et al., 2008; for a review Molinaro et al., 2011). The initial negative deflection has been interpreted as evidence for early detection of the morphosyntactic violation, and is thought to result from increased demand of operations related to syntactic integration operations. The later positivity has been associated with reanalysis and repair processes. Importantly, this early negativity and later positivity were observed within a sentence context. Outside a sentence context, agreement violations typically elicit a greater negativity at around 400 ms. After 500 ms, negative effects can be still present and no P600 effect has been reported (Münte & Heinze, 1994; Münte, Heinze & Mangun, 1993). Similarly, in the case of grammatical gender violation presented in isolation, an increased negativity at around 400 ms was observed when there was a mismatch between the gender of a transparent noun and the gender of a second word (i.e., an article: Barber & Carreiras, 2005, Exp.1; or an adjective: Barber & Carreiras, 2003; 2005, Exp.1).

Thus, while the time course of gender agreement processing has been widely investigated (Molinaro et al., 2011), no ERP study has tested whether the availability of formal cues has an effect on gender processing.

In this experiment, we examined the initial hemisphere-specific computations of gender agreement processing. Looking at each hemisphere's contribution to gender agreement processing allows us to check whether the system can detect the presence of formal gender cues (as assumed by the two-route model) or not. Specifically, positive evidence for the presence of a second form-based route to gender may be found during the left-hemisphere computations of gender agreement, given its specialisation in analysis of sub-lexical units.

A number of studies on hemispheric specialisation have observed that, while both hemispheres have grammatical abilities (Gazzaniga & Hillyard, 1971; Gazzaniga, Smylie, Baynes, Hirst, & McClery, 1984; Liu, Chiarello & Quan, 1999), the left hemisphere is more sensitive to the information conveyed by morphemes (Koenig, Wetzel & Caramazza, 1992) and it can carry out syntactic operations taking advantage of available sub-lexical units (Zaidel, 1983). Thus, if there is a form-based route that derives gender from the formal

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cues of words, it should be most evident in the left hemisphere during gender processing. Thus, we predict that the processing of transparent nouns will differ from that of opaque nouns particularly in the left hemisphere. To test this hypothesis, we employed a visual-half field presentation method, which is traditionally used to study the contribution of each hemisphere to language processing (Hellige, 1983). This paradigm takes advantage of the anatomical arrangement of the human visual system. As the nasal hemiretina projects contralaterally, stimuli briefly presented to the right or left of a central fixation point ($>.5°$) are initially/predominantly processed by the contralateral hemisphere. Although information presented in this way can be rapidly transmitted to both hemispheres, the hemi-field technique can be used to reveal initial hemisphere-specific computations (Federmeier, 2007). As a consequence, stimuli presented to the left visual field (LVF) are associated with the initial right-hemisphere computations (RH), and stimuli presented to the right visual field (RVF) are initially processed by the left hemisphere (LH).

This paradigm has been widely employed with split-brain patients (where the corpus callosum has been sectioned) and healthy participants, providing evidence for a clear LH advantage in morphosyntactic analysis. For example, Koenig et al. (1992) conducted a VHF study with healthy participants where they presented verbal stimuli to the LVF or to the RVF. These stimuli could be words or nonwords and participants had to perform a lexical decision task. Specifically, the nonwords were experimentally manipulated such that half of them were decomposable (made of a word stem plus suffix) and the other half were non-decomposable. The percentage of errors for decomposable nonwords was higher that for non-decomposable ones. This difference between these two types of nonwords was significant only for the RVF (LH) but not for the LVF (RH). Koenig et al. (1992) interpreted these results as suggesting that only the LH is able to detect morphologically decomposed forms.

Similarly, Zaidel (1983) reported experiments in which two split-brain patients were presented with lateralized images. After listening to correct sentences describing these images, they had to make grammatical number distinctions that could be expressed morphologically (e.g., the fish eats/the fish eat) or lexically (e.g., the fish is eating/the fish are eating). The LVF presentations (RH) showed lower accuracies with grammatical number distinctions that were signalled morphologically (e.g., the fish eats/the fish eat) than when they were signalled lexically (e.g., with the auxiliaries "is" or "are"). In contrast, the RVF presentations (LH) always showed high accuracies, without significant difference between the two conditions. A recent ERP study (Kemmer, Coulson, & Kutas, 2014) employed a similar experimental design. They presented sentences with number agreement violations that could be expressed either lexically (e.g., "The grateful niece asked herself/themselves how she could repay her aunt") or morphologically (e.g., "Industrial scientists develop/develops many new consumer products"). ERP responses were recorded while the target word (i.e., a pronoun or a verb) was presented to the LVF or to the RVF. While lexically marked violations elicited similar ERP correlates (i.e., P600 effect) for both VHFs, morphologically violations elicited a P600 effect only for the RVF presentations (LH). The authors interpreted the results as suggesting that both hemispheres can lexically compute agreement violations but the LH has a distinct advantage in detecting sub-lexical cues.

Given the LH advantage in sub-lexical analysis, the study of initial hemisphere-specific computations of gender processing allows testing of the hypothesis about the presence of two routes to gender.

1.1. The present study

We conducted an ERP study in which transparent and opaque Spanish nouns were each paired with an article, and the gender agreement between the two words was manipulated, resulting in agreeing and disagreeing word pairs. The VHF presentation method was employed. Specifically, while the article was always centrally presented, the noun was subsequently presented in the LVF (RH) or in the RVF (LH). Participants had to judge whether the noun agreed or not with the preceding article. Behavioural and ERP responses were recorded during the lateralized presentation. The recording of ERPs in combination with the visual-half field presentation has been used successfully in previous studies on lexico-semantic processing (Federmeier, Mai & Kutas, 2005; Federmeier, Wlotko, & Meyer, 2008), and recently, this method has also been used to study syntactic processing (Kemmer et al. 2014).

Given the results from VHF studies of patients (Zaidel, 1983) and healthy subjects (Liu et al., 1999), both hemispheres should be able to compute agreement dependencies and to detect agreement violations. Thus, behavioural and ERP effects for gender agreement should be observed for each visual half field. Specifically, a behavioural cost (i.e., slower and less accurate responses) and a greater negativity at around 400 ms was expected in response to gender agreement violations both for LVF and for RVF, as already observed for gender mismatch in isolated word pairs with central presentation (Bates et al., 1996; Barber & Carreiras, 2003; 2005, Exp.1; Münte & Heinze, 1994).

We also expected behavioural and ERP differences between transparent and opaque nouns, confirming the presence of two different routes to grammatical gender (Gollan & Frost, 2001). Specifically, a behavioural advantage for transparent nouns as compared to opaque nouns was expected, particularly and perhaps uniquely for RVF (LH) presentations. It is hard to predict which ERP components will be most different between the two hemispheres for transparent compared to opaque nouns, since this is the first ERP study directly comparing transparent and opaque nouns.

Given its excellent temporal resolution, ERP is a particularly suitable method for revealing the presence of hemispheric differences in the time course of the second form-based route (reflected by an interaction between VHF and transparency). The LH may demonstrate early sensitivity to distributional cues conveyed by the word ending, given the LH advantage for sub-lexical information processing (Koenig et al., 1992; Zaidel, 1983; Kemmer et al., 2014). By contrast, the RH should not be sensitive at all or, at least, should be less skilled in detecting formal cues to gender (Gazzaniga & Hillyard, 1971; Gazzaniga et al., 1984; Koenig et al., 1992; Liu et al., 1999; Kemmer at al., 2014). Thus, the ERPs evoked by transparent and opaque nouns may not differ for LVF (RH) presentations, or may differ in later ERP components than the differences observed for RVF (LH) presentations.

2. Material and methods

2.1. Participants

Thirty-two native Spanish speakers participated in the experiment as volunteers (17 women and 15 men). Ages ranged from 18 to 41 (mean age 25.5 years; SD 7). None had exposure to any other language before the age of four. All participants were right-handed, and the mean handedness quotient was .86 (range: .5–1) as assessed by the Spanish version of the Edinburgh Inventory (Oldfield, 1971), where "1" is strongly right-handed and "-1" is strongly left-handed. Participants reported normal or corrected-to-normal vision and had no history of neurological disorders.

2.2. Materials

A list of 160 Spanish transparent nouns was selected, where 80 nouns were masculine and 80 nouns were feminine. The masculine

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nouns ended with "-o", which is the typical Spanish ending for masculine (e.g., *queso*, "cheese$_m$"), while the feminine nouns showed the typical feminine ending "-a" (e.g., *playa*, "beach$_f$"). Irregular nouns were excluded. Next, another list of 160 opaque nouns was created selecting words whose ending (i.e., "-e", "-n", "-l", "-s", "-j", "-r", "-d", "-z") was not informative of the grammatical gender. The nouns ending in groups of letters that are strongly associated with a specific gender class (e.g., "-sis", "-tis", "-í", "-briz", "-triz", "-driz", "-ie", "-umbre"; according to Bull, 1965; Clegg, 2010) were excluded. Again, half of the opaque nouns were masculine (e.g., *reloj*, "clock$_m$") and the other half feminine (e.g., *flor*, "flower$_f$").

The mean number of letters for transparent and opaque nouns was identical (mean: 5.92 letters, SD=1.32; $t(159) < 1$, $p=1$; range: 4–8 letters). The frequency of use extracted with *BuscaPalabras* (Davis & Perea, 2005) was similar between the two groups of nouns (mean log-transformed values of frequency 1.37 for both types of nouns, with a SD of .54 for transparent nouns and .58 for opaque ones; $t(159) < 1$, $p=.78$). In addition, transparent and opaque nouns did not differ for measures of concreteness (transparent nouns; mean: 4.86, SD=1.10; opaque nouns: mean: 4.80, SD=1.20; $t(159) < 1$, $p=.82$; these measures were extracted using *BuscaPalabras*, Davis & Perea, 2005). Overall, we had 320 Spanish nouns. Nouns referring to entities with a biological gender (e.g., professions or animals) were excluded from the experimental stimuli in order to avoid any possible interaction between the grammatical gender information and the conceptual information concerning the sex of the referent (Vigliocco & Frank, 1999).

Then, each noun was paired once with the masculine article *el* and once with the feminine article *la*, resulting in 640 word pairs. As seen in previous VHF studies (Faust, Kravetz, Babkoff, 1993; Liu et al., 1999), the prime (i.e. article) was centrally presented. Each target (i.e., noun) was randomly presented in a lateralized position: once to the left visual field (LVF) and once to the right visual field (RVF). In this way, participants cannot make predictions about the location of the noun, and therefore cannot move their gaze to that side before the target presentation. The experimental manipulation of transparency, agreement and VHF resulted in eight experimental conditions (see Table 1).

Four different lists of 320 trials each were created in order to avoid repeated presentations. Target nouns were rotated across lists following a Latin square design such that each noun occurred only in one of the eight experimental conditions. A list contained eight conditions of 40 trials each, where nouns were balanced for lexical factors (length: $F(7, 319)= 1.84$, $p=.78$; frequency: $F(7, 319)= .58$, $p=.77$). Different participants were assigned to each list so that they could not see the same target noun repeated in different conditions.

2.3. Procedure

Participants were seated in a dark sound-proof chamber, 120 cm away from the computer monitor. A chinrest was also used in order

Table 1
Sample of article–noun pairs for the eight experimental conditions.

Transparent nouns		
	LVF	**RVF**
Agreement	*el queso* (The$_m$ cheese$_m$)	*el queso* (The$_m$ cheese$_m$)
Disagreement	*la queso* (The$_f$ cheese$_m$)	*la queso* (The$_f$ cheese$_m$)
Opaque nouns		
	LVF	**RVF**
Agreement	*el reloj* (The$_m$ clock$_m$)	*el reloj* (The$_m$ clock$_m$)
Disagreement	*la reloj* (The$_f$ clock$_m$)	*la reloj* (The$_f$ clock$_m$)

to minimise head movements, and to maintain a constant viewing distance. Stimuli were displayed in yellow letters against a black background in order to minimise the contrast between colours and to facilitate the task of reading. Participants were asked to judge the grammatical gender agreement between the article and the noun. Each trial began with a fixation cross in the centre of the screen for 2000 ms, and this was followed by a blank screen of 200 ms. Then the article appeared in a central position for 200 ms and was followed by a 750-ms blank interval. Finally, the target noun appeared for 200 ms in the left or in the right visual field such that the inner edge of the word was 2° of visual angle from the centre of the screen. After the lateralized noun presentation, participants had 3000 ms to judge the correctness of gender agreement between the article and the noun. They were instructed to respond by pressing one of two buttons on the keyboard. Each hand had one response button and the button position was counterbalanced across participants. Numbers of correct responses were recorded, and RTs were calculated in milliseconds from the onset of the target noun to the participant's key press.

Participants were instructed to minimise blinks, eye movements and muscle activity while reading and to maintain central fixation during the lateralized presentation.

There were 20 practice trials to ensure that participants understood the instructions. The experimental session was divided in four blocks with a short break between blocks. All trials were presented in a different random order for each participant.

To make sure that participants paid attention to the stimuli, at the conclusion of the recording session they were given a recognition memory test consisting of 40 nouns: 20 new and 20 that had been presented in the experiment. Participants were asked to classify each word as new or old.

2.3.1. Electrophysiological recordings and analyses

EEG was recorded from 27 Ag/AgCl electrodes placed in an elastic cap (Easycap, www.easycap.de): Fp1, Fp2, F7, F8, F3, F4, FC5, FC6, FC1, FC2, T7, T8, C3, C4, CP5, CP6, CP1, CP2, P3, P4, P7, P8, O1, O2, Fz, Cz, Pz. All sites were online referenced to the left mastoid (A1). Additional external electrodes were placed on mastoids (A1, A2) and around eyes (Ve1, Ve2, He1, He2). Horizontal and vertical electrodes were referenced to each other. Data were recorded and amplified with a bandwidth of .01–100 Hz at a sampling rate of 250 Hz. Electrode impedance was kept below 5 kΩ for scalp electrodes, and below 10 kΩ for the four eye channels. EEG recordings were re-referenced off-line to the average activity of the left and right mastoid. The offline filtering consisted of a low cutoff filter of .2 Hz and a high cutoff of 20 Hz. Eye movements were recorded for later off-line rejection of contaminated trials. The horizontal electrooculogram (EOG), recorded as the voltage difference between electrodes placed lateral to the external canthi, was used to measure horizontal eye movements. The vertical EOG, recorded as the voltage difference between electrodes placed above and below the eyes, was used to detect blinks and vertical eye movements. Artefacts exceeding ±100 μV in amplitude were rejected. Blinks were corrected following the procedure proposed by Gratton, Coles, and Donchin (1983) only when there was an excessively high number of ocular artefacts (more than 10% of rejection rate). Two participants were excluded from the following analyses given the high number of rejected epochs (more than 20%). In the remaining participants, there were no differences in the number of rejections between conditions ($F(7, 232) < 1$; $p=.81$). On average, 14% of trials were excluded from further analysis. Epochs of 1100 ms (from −100 ms to 1000 ms) were obtained for each of the target words, including a 100-ms prestimulus baseline. For each condition, the average ERP waveforms were computed time-locked to the onset of the target noun in each hemifield. EEG analyses were conducted only on the trials in which participants responded correctly.

Based on previous studies using central presentation (e.g., Barber & Carreiras, 2003), two different time windows were selected: 350–500 ms; 500–750 ms. Statistical analyses were carried out using the mean voltage during noun presentation (which was averaged across time points within the two different time windows as measured from noun onset) as the dependent variable.

ERP effects were evaluated taking into account nine clusters of electrodes. Each cluster represented the mean amplitude of three electrodes in proximate positions: Left Anterior (F3, F7, FC5), Left Central (C3, T7, CP5), Left Posterior (P3, P7, O1), Medial Anterior (Fp1, Fp2, Fz), Medial Central (FC1, FC2, Cz), Medial Posterior (CP1, CP2, Pz), Right Anterior (F4, F8, FC6), Right Central (C4, T8, CP6), Right Posterior (P4, P8, O2). These clusters were included in the statistical analyses as different levels of two topographical factors: anteriority (anterior, central and posterior) and laterality (right, medial and left). Repeated measures analyses of variance (ANOVA) were performed with the three experimental variables (transparency, agreement and visual field) and the two topographical factors (anteriority and laterality) as within-subject factors. Effects of the two topographical factors will only be reported when they interact with the experimental manipulations. The Greenhouse–Geisser procedure was applied where the sphericity assumption was violated.

3. Results

3.1. Behavioural results

3.1.1. Gender agreement judgment

Accuracies (mean percentage of correct responses) and reaction times (RTs) from accurate trials were analysed using a three-way repeated measures ANOVA with two levels of transparency (transparent, opaque), two levels of agreement (agreement, disagreement) and two levels of VHF (RVF, LVF) as factors. For both RTs and accuracy data two ANOVAs were conducted: one by participants (F_1) and one by items (F_2). In the design by participants all factors were within-participant. In the design by items, agreement and VHF were within-item factors, whereas the factor of transparency was treated as between items. Mean accuracies and RTs for each experimental condition are given in Table 2.

For the accuracy, there was a significant main effect of agreement (F_1 (1, 29)=10.13, p <.01; F_2 (1, 318)=24.48, p <.001). Specifically, the agreement condition showed a higher accuracy than the disagreement one. The effect of VHF was also significant (F_1 (1, 29)=7.65, p <.05; F_2 (1, 318)=13.06, p <.001), with more correct responses for the RVF as compared with the LVF. Finally, the effect of transparency reached significance (F_1 (1, 29)=31.06, p <.001; F_2 (1, 318)=17.62, p <.001): participants made fewer errors with transparent nouns than with opaque nouns. None of the interactions between these factors reached significance.

A similar analysis was conducted on RTs, a main effect of agreement was observed (F_1 (1, 29)=24.00, p <.001; F_2 (1, 316)=70.61, p <.001) with faster responses in the agreement condition than in the disagreement one. VHF factor was also significant (F_1 (1, 29)=19.02, p <.001; F_2 (1, 316)=54.15, p <.001) where participants were faster to respond to RVF presentations than to LVF presentations. The effect of transparency did not reach significance (F_1 and F_2 < 1). The higher level interactions were not significant.

3.1.2. Recognition memory test

Participants correctly identified as "old" 67.2% of the target nouns on the recognition test, with an average of false alarms of 38.8% (d'= 4.88, SD=1.32). The percentage of correct recognition was significantly different from the false alarm rate (t(29)=23.61, p <.001; the d' value was also significantly different from zero: t (29)=20.19, p <.001) indicating that participants paid attention to the experimental stimuli and were able to discriminate between the words and distractors.

3.2. Event-related potentials

Figs. 1 and 2 show ERPs for RVF and LVF presentations respectively. In each figure, the waveforms show the main effects of agreement and transparency.

The topographic distribution of average potentials is shown by the scalp maps. Visual inspection in both hemifields revealed a negativity peaking around 400 ms, followed by an extended late negativity between 500 ms and 750 ms for both main effects. However, for each of the two time windows (350–500 ms, and 500–750 ms), hemispheric differences are evident especially for the transparency effect.

Specifically, transparent nouns showed a sustained negativity with greater amplitude than opaque nouns only for RVF presentations (LH; see Fig. 1, right side) and not for LVF presentations (RH; see Fig. 2, right side). Both LH and RH showed an increased negativity at around 400 ms for the disagreement condition compared to the agreement condition.

In order to investigate the hemispheric differences qualitatively described above, statistical analyses were carried out for the time windows: 350–500 ms and 500–750 ms. Mean voltage measures were subjected to an omnibus ANOVA with transparency, agreement, VHF, anteriority and laterality as factors. In the description of the results, significant higher-level interactions will only be reported when they include the VHF factor in order to focus on the hemispheric differences during gender agreement processing.

In the 350–500 ms time window, the analysis revealed main effects of agreement (F (1, 29)=17.55, p <.001) and transparency

Table 2
Mean RTs and percentage of correct responses per condition. Standard deviations are given in parenthesis. Differences for RTs were computed subtracting disagreement and agreement condition (rows), LVF and RVF (columns). For the accuracy the reverse order was used.

	RTs		***Difference***	**Accuracy**		***Difference***
	LVF	**RVF**		**LVF**	**RVF**	
Transparent nouns						
Agreement	950 (2 4 4)	898 (2 4 4)	52	91 (6)	93 (5)	2
Disagreement	1003 (2 6 5)	961 (2 2 2)	42	89 (9)	91 (7)	2
Difference	53	63		2	2	
Opaque nouns						
Agreement	960 (2 5 8)	893 (2 3 1)	67	88 (10)	91 (7)	3
Disagreement	1031 (2 6 9)	959 (2 4 3)	72	83 (11)	86 (9)	3
Difference	71	66		5	5	

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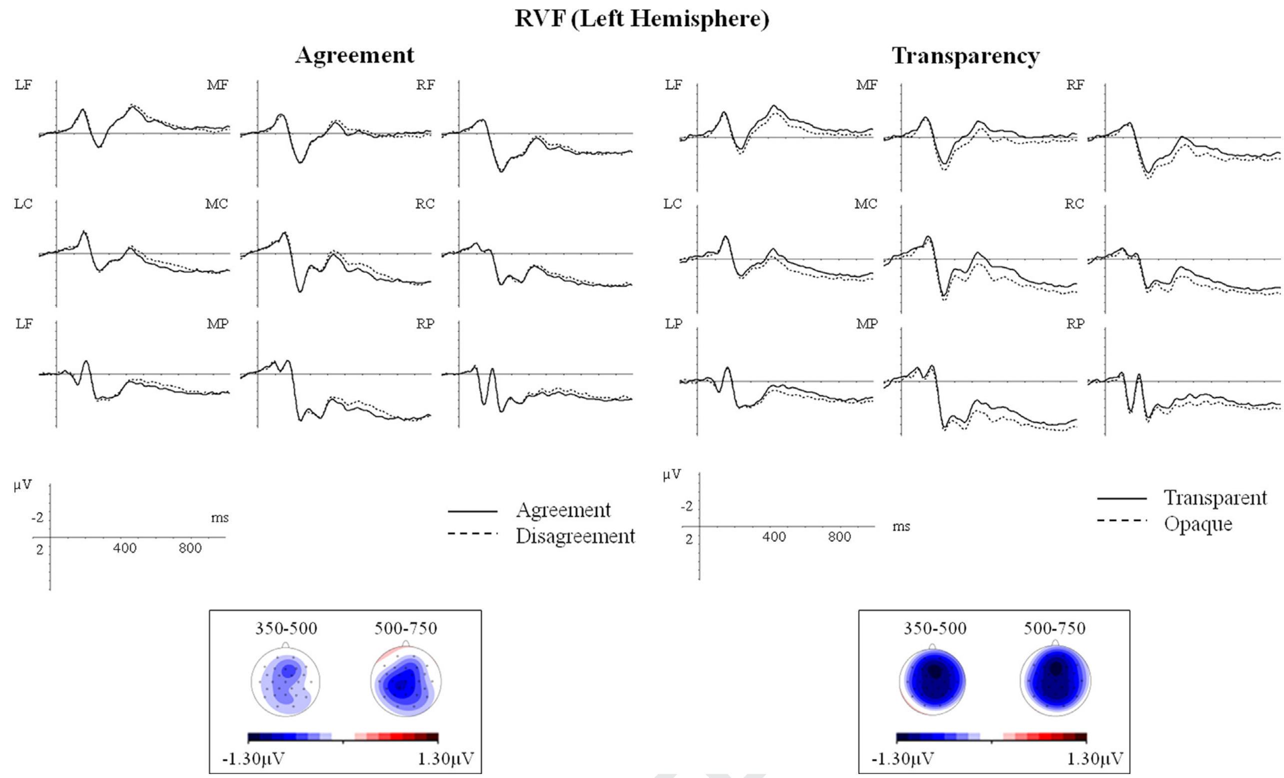

Fig. 1. Grand averages of the RVF target nouns were represented for agreement (left side) and transparency (right side). Each graph represents the average of one electrode cluster: LF (Left Frontal), MF (Medial Frontal), RF (Right Frontal), LC (Left Central), MC (Medial Central), RC (Right Central), LP (Left Posterior), MP (Medial Posterior), RP (Right Posterior). Negativity is plotted upwards. The topographical maps were computed from the values resulting from the subtraction waves (disagreement minus agreement condition; transparent minus opaque condition) in the 350–500 and 500–750 ms time windows.

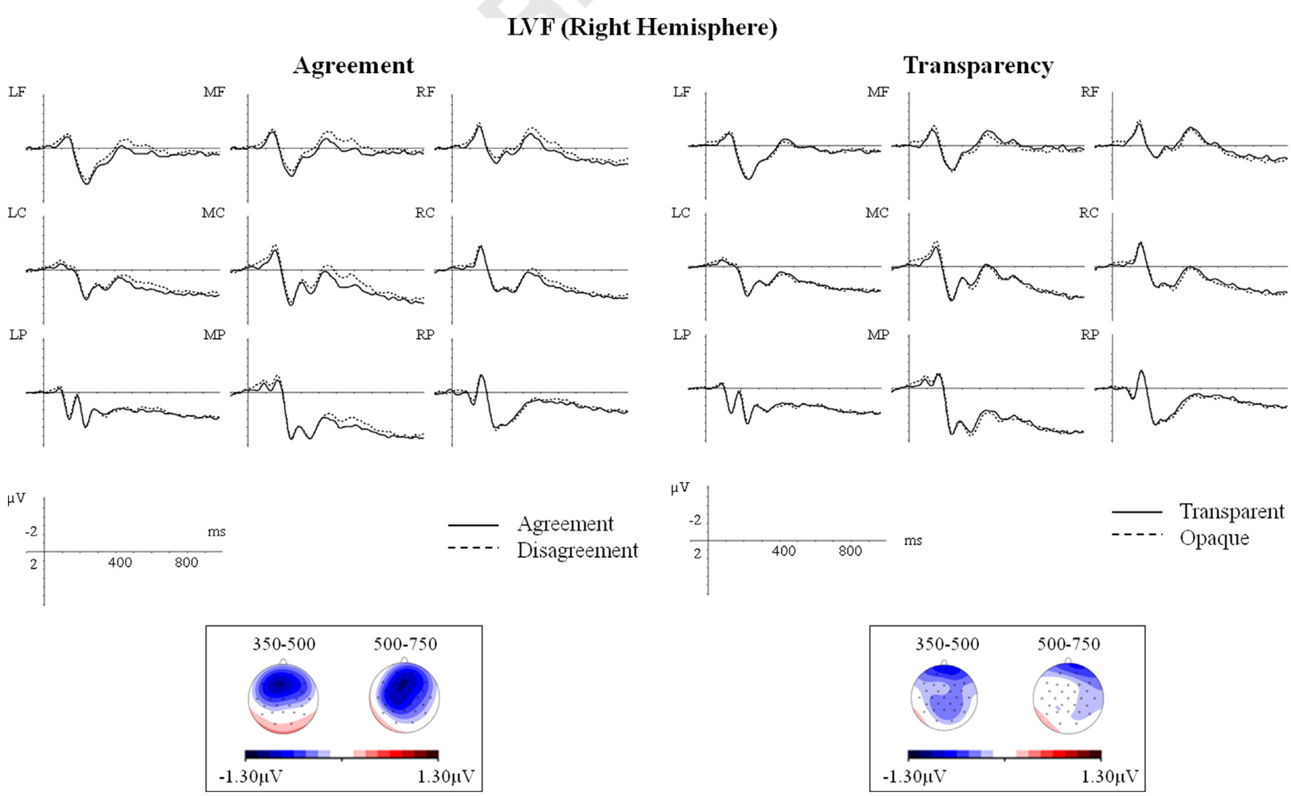

Fig. 2. Grand averages of the LVF target nouns were represented for agreement (left side) and transparency (right side). Each graph represents the average of one electrode cluster: LF (Left Frontal), MF (Medial Frontal), RF (Right Frontal), LC (Left Central), MC (Medial Central), RC (Right Central), LP (Left Posterior), MP (Medial Posterior), RP (Right Posterior). Negativity is plotted upwards. The topographical maps were computed from the values resulting from the subtraction waves (disagreement minus agreement condition; transparent minus opaque condition) in the 350–500 and 500–750 ms time windows.

($F(1, 29)=17.55$, $p<.001$). The VHF factor significantly interacted with the two topographical factors (VHF x laterality: $F(2, 58)=17.62$, $p<.001$; VHF x laterality x anteriority: $F(4, 116)=6.29$, $p<.05$), indicating that lateralized presentation influenced ERP scalp topography with larger negative potentials over electrode sites contralateral to the VHF of presentation. There was also a significant interaction between VHF, agreement and anteriority ($F(2, 58)=7.13$, $p<.01$) and a marginally significant interaction between VHF and transparency ($F(1,29)=3.91$, $p=.06$) suggesting that the manipulations of agreement and transparency differently affected the ERPs recorded during LVF and RVF presentations. Specifically, the effect of agreement seems to be more anteriorly distributed for the RVF than for the LVF and the effect of transparency seems to be present only for the RVF.

In the second time window (500–750 ms), a main effect of agreement ($F(1, 29)=19.03$, $p<.001$) and transparency ($F(1, 29)=10.41$, $p<.01$) were observed. The interaction between VHF and laterality continued to be significant ($F(2, 58)=15.18$, $p<.001$). As in the first time window, the VHF factor significantly interacted with transparency (VHF x transparency x laterality: $F(2, 58)=3.24$, $p<.05$) and with agreement (VHF x transparency x agreement: $F(1, 29)=7.88$, $p<.01$), suggesting that the hemifield of presentation modulated the effects of these two experimental factors. Finally, the five-way interaction was significant (VHF x transparency x agreement x laterality x anteriority: $F(4, 116)=3.88$, $p<.05$).

In summary, the general ANOVA revealed significant main effects of agreement and transparency in both time windows. These factors significantly interacted with the VHF factor, suggesting the presence of hemispheric differences in the ERP responses to agreement and transparency manipulations. In order to better understand what happened in each hemisphere over time, separate ANOVAs were carried out for each visual field including agreement, transparency, anteriority and laterality as factors.

3.2.1. RVF (left hemisphere)

Fig. 3 shows ERP responses evoked by the target nouns presented to the RVF in each experimental condition.

3.2.1.1. 350–500 ms window. The analysis revealed a main effect of agreement ($F(1, 29)=4.94$, $p<.05$) with more negative amplitudes for the disagreement condition than the agreement condition (see Fig. 3, top row). There was also a main effect of transparency ($F(1, 29)=22.73$, $p<.001$), indicating that transparent nouns elicited more negative response than opaque nouns (see Fig. 3, bottom row). A significant interaction between transparency and laterality was also observed ($F(2, 58)=6.01$, $p<.01$), suggesting that the transparency effect size was greater for medial and right electrode sites compared with left sites (medial vs. left, $t(29)=3.77$, $p<.001$; right vs. left, $t(29)=1.79$, $p=.09$; right vs. medial, $t(29)=1.52$, $p=.14$). The interaction between agreement and transparency was not significant ($F<1$).

3.2.1.2. 500–750 ms window. The ANOVA showed a main effect of agreement ($F(1, 29)=9.70$, $p<.01$) with an increased negativity for the disagreement condition than the agreement condition (see Fig. 3, top row). There was also a main effect of transparency ($F(1, 29)=30.78$, $p<.001$), suggesting that transparent nouns were more negative than opaque nouns (see Fig. 3, bottom row). There was again a significant interaction transparency x laterality ($F(2, 58)=5.71$, $p<.01$) indicating that the effect was more prominent over medial sites (medial vs. left, $t(29)=3.22$, $p<.01$; medial vs. right, $t(29)=3.23$, $p<.01$; right vs. left, $t(29)<1$, $p=.57$). No interaction emerged between agreement and transparency ($F(1, 29)=1.80$, $p=.19$).

3.2.2. LVF (right hemisphere)

Fig. 4 shows ERP responses evoked by the target nouns presented to the LVF in each experimental condition.

3.2.2.1. 350–500 ms window. The analysis yielded a significant main effect of agreement[1] ($F(1, 29)=5.76$, $p<.05$), with greater negativities for the disagreement condition than the agreement condition (see Fig. 4, top row). The agreement effect also interacted with anteriority ($F(2,58)=7.96$, $p<.01$) and laterality ($F(2,58)=4.12$, $p<.05$), indicating that the effect was located in central and anterior electrodes (both $p<.01$; posterior sites: $p=.99$) and was greater over medial sites (medial vs. left, $t(29)=2.31$, $p<.05$; medial vs. right, $t(29)=2.40$, $p<.05$; right vs. left, $t(29)<1$, $p=.44$). There was no main effect of transparency ($F(1,29)=2.57$, $p=.12$; see Fig. 4 bottom row) and no significant interaction with the topographical factors (transparency x anteriority: $F<1$; transparency x laterality: $F(2,58)=1.30$, $p=.28$; transparency x laterality x anteriority: $F<1$). The factors of transparency and agreement did not significantly interact ($F<1$).

3.2.2.2. 500–750 ms window. A main effect of agreement was observed ($F(1, 29)=9.80$, $p<.01$), with an increased negativity for the disagreement condition compared to the agreement condition (see Fig. 4, top row). There was also a significant interaction between agreement and laterality ($F(2, 58)=3.90$, $p<.05$), suggesting that the agreement effect was greater over medial electrode sites (medial vs. left, $t(29)=2.52$, $p<.05$; medial vs. right, $t(29)=2.83$, $p<.01$; right vs. left, $t(29)<1$, $p=.89$). There was no main effect of transparency ($F(1, 29)<1$, $p=.53$; see Fig. 4, bottom row). Significant interactions between transparency and agreement were found, suggesting that the agreement effect differed between transparent and opaque nouns (transparency x agreement: $F(1, 29)=6.95$, $p<.05$; transparency x agreement x laterality x anteriority emerged: $F(4, 116)=3.41$, $p<.05$). Specifically, post-hoc tests on the mean voltage revealed that the disagreement condition was more negative than the agreement condition for transparent nouns ($p<.01$; see Fig. 4, top row, left side), but not for opaque nouns ($p=.43$; see Fig. 4, top row, right side). Disagreeing opaque nouns were also more negative than agreeing transparent nouns ($p<.01$). None of the other post-hoc comparisons reached significance.

In summary, the LH showed a similar pattern of response in both time windows: an effect of gender agreement and a central-distributed transparency effect. In contrast, the RH showed only an effect of agreement with central–anterior distribution between 350 and 500 ms. During the second time window, the effect of gender agreement could only be observed for transparent nouns.

4. Discussion

The current ERP study examined gender agreement processing in Spanish article–noun word pairs in order to provide evidence for the existence of two routes for gender retrieval. Article–noun pairs could agree or not in gender. Noun transparency was manipulated such that nouns could be transparent or opaque. The VHF method was employed in order to disentangle the initial hemisphere-specific computations of gender processing. Behavioural and ERP measures were recorded in response to the target nouns.

[1] Point-by-point analyses in the 0–200 ms time window showed only short-lasting significant differences (< 50 ms) in isolated electrode sites.

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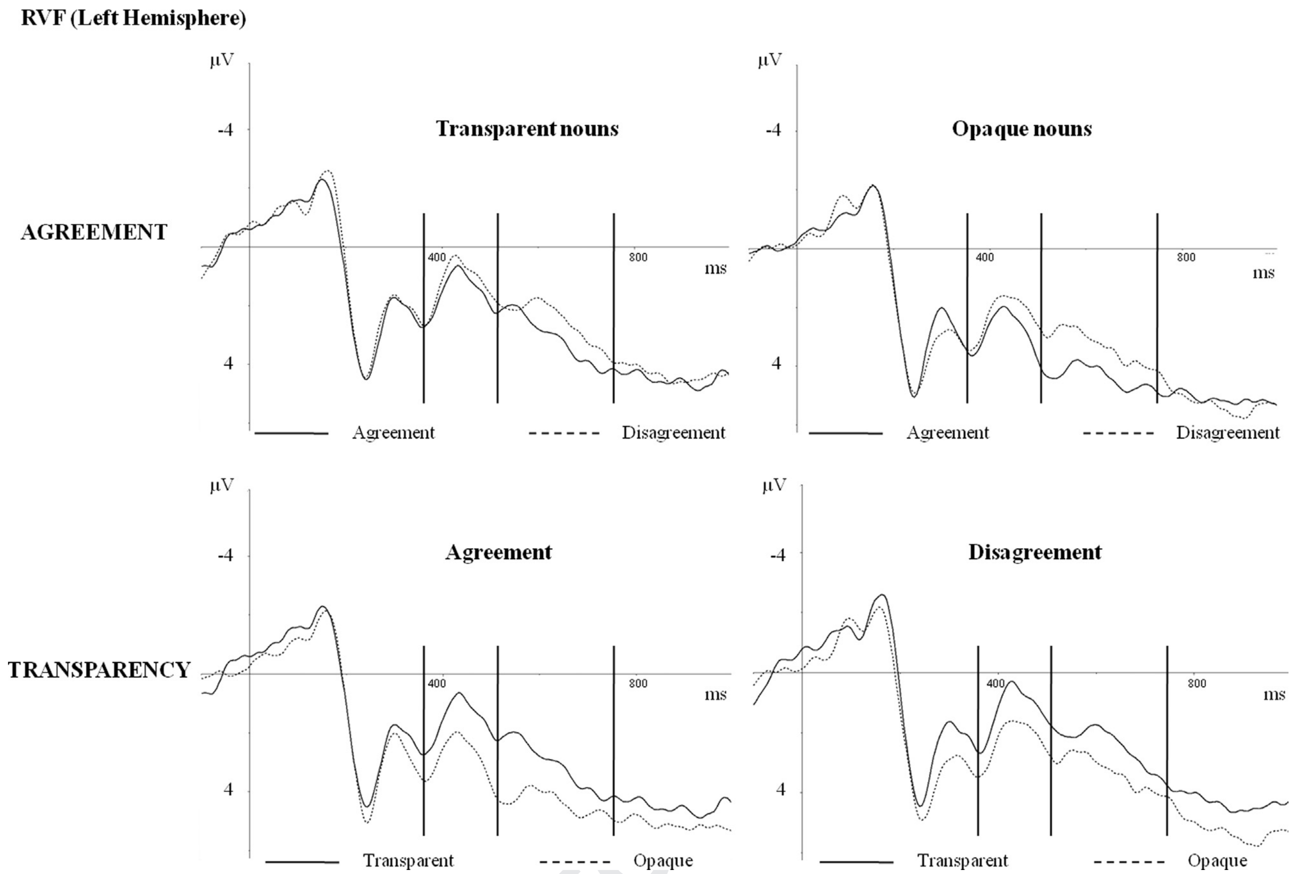

Fig. 3. ERPs to the target nouns for the RVF. Since some of the effects we found were prominent over medial sites, Cz electrode is shown as a representative electrode for each condition. Agreement and disagreement conditions are compared above (full and dashed lines, respectively) for each level of transparency factor. Transparent and opaque nouns are compared below (full and dashed lines, respectively) for each level of agreement factor. Negativity is plotted upwards. Vertical lines mark the two time windows analysed.

In line with our previous hypotheses, the results showed that experimental manipulations of agreement and transparency produced significant effects in behavioural and ERP measures.

At the behavioural level, participants were faster and more accurate in the agreement than in the disagreement condition. Moreover, higher accuracies were observed for transparent nouns as compared with opaque nouns. The VHF manipulation also had a significant effect, with faster responses and higher accuracy observed for RVF compared to LVF presentations.

The ERP results were in line with our hypotheses, showing a main effect of agreement and transparency in the two time windows analysed: 350–500 ms and 500–750 ms. Specifically, a greater negativity was elicited by the disagreement condition than by the agreement condition. Moreover, transparent nouns showed greater negative amplitudes compared with opaque nouns.

In addition, each of the agreement and transparency factors significantly interacted with the VHF factor in both time windows (350–500 ms and 500–750 ms) suggesting the presence of hemispheric differences in the time course of gender processing. We predicted that transparency effects should have been clearly present in the case of RVF presentations (LH), while transparency effects could be absent or, at least, delayed in the case of LVF presentations (RH). That was what we found: the LH showed an effect of transparency (and gender agreement) in both time windows, while the RH showed a main effect of agreement in the 350–500 ms time window, which continued to be significant only for transparent nouns in the 500–750 ms time window.

Considering the behavioural results, the experimental manipulation of gender agreement elicited similar effects for both LVF and RVF presentations. Specifically, for both hemifields, the disagreement condition was associated with slower and less accurate responses, suggesting that both hemispheres can detect gender mismatches in word pairs, and items with gender disagreement are more difficult to process than agreeing items. This finding confirms that observed in a previous VHF study on grammatical agreement (Liu et al., 1999), and similar behavioural effects were found with word pairs centrally presented while participants had to perform a grammaticality judgment (Bates et al., 1996; Gollan & Frost, 2001). In addition, our behavioural findings showed an advantage for RVF presentations, which is traditionally interpreted as reflecting LH dominance for language processing (Chiarello, Liu, Shears, Quan & Kacinik, 2003; Faust, Bar-lev & Chiarello 2003; Liu et al., 1999). It seems unlikely that this effect could be due to left–right reading direction because VHF studies have been carried out also with languages read from right to left (e.g. Hebrew or Arabic) and they showed the same RVF behavioural advantage during processing of a target word presented in isolation (Almabruk, Paterson, McGowan, & Jordan, 2011; Babkoff, Faust, & Lavidor, 1997; Faust et al.1993; Ibrahim, & Eviatar, 2009) or preceded by a prime displayed at the centre of the screen (Faust et al., 1993). Moreover, this RVF advantage seems to be specifically related to the processing of linguistic information, rather than to attention shifts during reading, since it has been found with words, but not with pseudo-words (Jordan, Fuggetta, Paterson, Kurtev & Xu, 2011).

Interestingly, we also found a significant effect of noun transparency, with higher accuracies for the transparent nouns than opaque nouns. This is in line with behavioural measures on transparent and

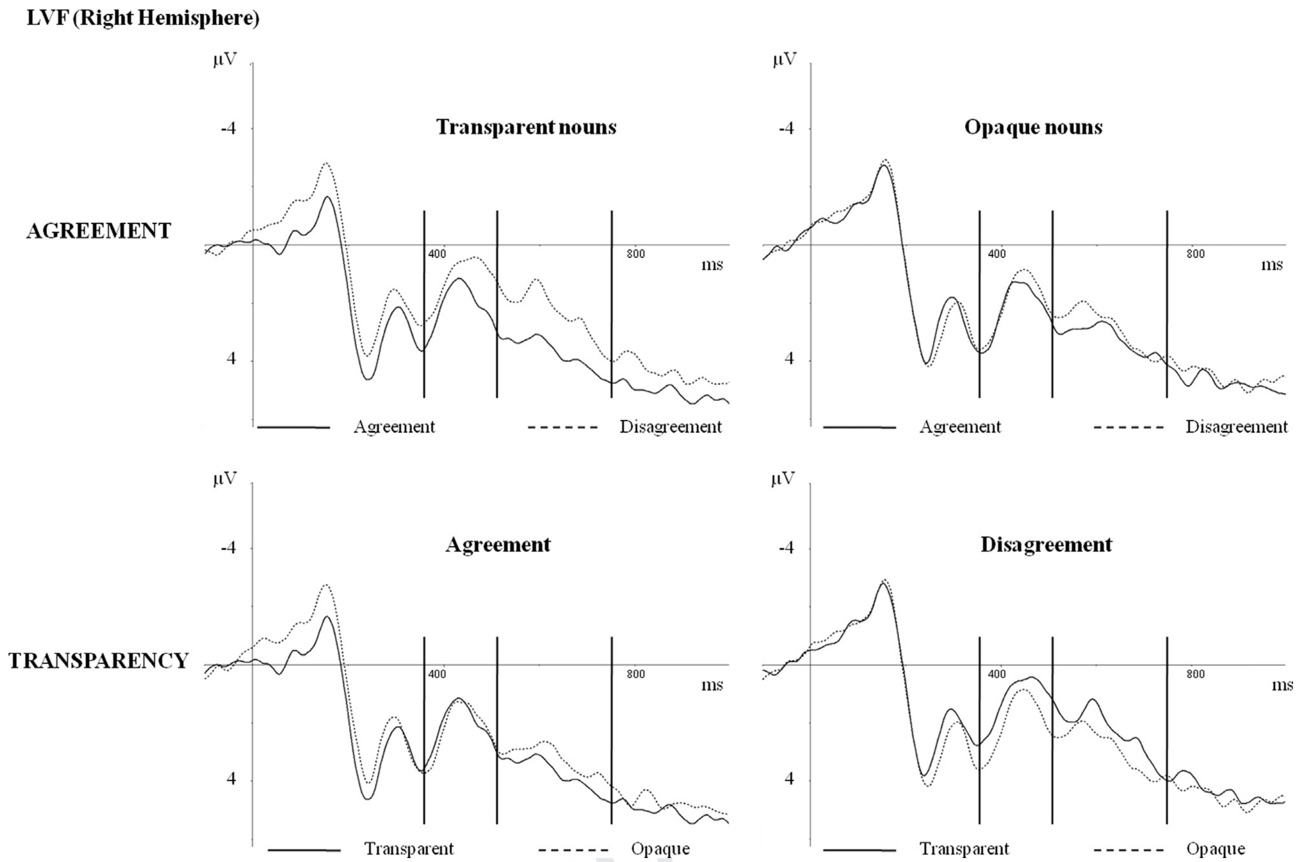

Fig. 4. ERPs to the target nouns for the LVF. Since some of the effects we found were prominent over medial sites, Cz electrode is shown as a representative electrode for each condition. Agreement and disagreement conditions are compared above (full and dashed lines, respectively) for each level of transparency factor. Transparent and opaque nouns are compared below (full and dashed lines, respectively) for each level of agreement factor. Negativity is plotted upwards. Vertical lines mark the two time windows analysed.

opaque nouns centrally presented (Bates, et al., 1995; 1996; Gollan & Frost, 2001; Hernandez et al., 2004; Taft & Meunier 1998). This main effect of transparency provides evidence that participants rely on formal cues to gender when they are available, as suggested by the two-route model (Gollan & Frost, 2001).

Moreover, analysis of the EEG data recorded in this VHF study revealed the lateralized contribution of gender processing as it unfolds over time. For both hemifields we found that gender agreement violations evoked an increased negativity at around 400 ms as compared with the agreement condition. On the basis of its time course and topography, this ERP effect can be interpreted as an N400-type effect, which has been previously observed with Spanish word pairs presented in a central position and is considered a reflection of word integration processes that build higher-order representations (Barber & Carreiras, 2003; 2005, Exp.1; Münte & Heinze, 1994). Specifically, this effect seems to reflect integration processes of different features associated with lexical representations (e.g., grammatical gender) and its distribution seems to vary depending on the types of vocabulary classes involved (a central posterior distribution with noun–adjective gender violations: Barber & Carreiras, 2003; 2005, Exp.1; a broader distribution which also covers anterior areas in the case of article–noun gender mismatch: Barber & Carreiras, 2005, Exp.1; Münte & Heinze, 1994). While previous ERP studies on gender agreement violations in word pairs have reported an increased negativity between 300 ms and 500 ms (Barber & Carreiras, 2003; 2005, Exp.1), the agreement effect in the present study lasts until 700 ms. Methodological differences between studies could account for this long-lasting negativity. For instance, while in the present study the target word was presented for 200 ms in a lateralized position, previous studies presented the noun in a central position for 300 ms. The brief lateralized presentation of the target noun could have made the grammaticality judgement task more difficult, resulting in a long-lasting processing of gender agreement. The presence of this negative effect for both hemifields suggests that both hemispheres can integrate the lexical information necessary for detecting gender mismatch. These data are in line with a recent meta-analysis of neuroimaging studies, which showed that syntactic manipulations trigger an activation of the inferior frontal gyrus in both LH and RH (Vigneau et al. 2011).

Interestingly, there was no interaction between transparency and agreement effects, at least in the first time window, suggesting that the initial computation of grammatical agreement does not rely on distributional information conveyed by the word ending. In other words, the presence of gender-related endings does not seem to influence the way in which the system initially computes agreement dependencies. Consistent with this conclusion, recent MEG data on gender agreement processing suggested that the initial computation of gender agreement relies on a lexical information source (Molinaro, Barber, Pérez, Parkkonen, & Carreiras, 2013). The early effect observed for gender mismatches could possibly reflect the initial interference between the determiner and the gender feature of the noun retrieved as an abstract feature stored in the lexicon. The present findings would further suggest that both hemispheres can retrieve gender information as a lexical feature in order to compute agreement dependencies (see Kemmer et al. 2014, for similar results on number agreement).

The ERP data recorded during lateralized presentations also suggests that the two hemispheres differ in the way they deal with the available formal cues to gender and provides evidence for a hemispheric difference in the time course of noun transparency processing. Critically, between 350–500 ms the LH showed a greater negativity for transparent nouns than opaque nouns; while the RH hemisphere did not show any effect of transparency in the first time window. This long-lasting negativity observed for the transparency effect during the LH computations could be interpreted as reflecting different working memory demands (Ruchkin, Johnson, Mahaffey, Sutton, 1988). In fact, while in the case of transparent nouns two different sources of information are available (i.e., lexical and form-based), in the case of opaque nouns only the lexical route can be used. This difference in the amount of available information that needs to be integrated could account for the ERP difference reported between transparent and opaque nouns.

The present findings confirm the idea that transparent and opaque nouns are computed differently during gender processing and represent the first ERP evidence for the presence of two routes to grammatical gender (Gollan & Frost, 2001). Consistent with previous behavioural results (Bates et al., 1995; Exp.1; 1996, Exp. 2, 3; Gollan & Frost, 2001; Hernandez et al., 2004; Taft & Meunier, 1998), our ERP data suggest that the lexical route is not the only way to recover grammatical gender, but that there is also a second form-based route, which uses the strong correlations between the gender of a noun and its word form to access gender. When transparent endings are available, they represent a reliable cue for gender retrieval. In contrast, when no formal cues are available (as in the case of opaque nouns) the lexical route is the only way to retrieve gender information and compute agreement dependencies. Thus, the present ERP study confirms Gollan and Frost's hypothesis and provides further information about the time course of the form-based route. The effect of noun transparency would suggest that the form-based route can be activated as early as 350 ms after the stimulus onset. This onset would suggest that distributional information conveyed by the noun ending can be available early on and it seems possible for the form-based route to work in parallel with the lexical route.

While the LH is sensitive to distributional cues conveyed by the word ending at an early stage (350–500 ms), the RH showed an influence of noun transparency only after 500 ms. Specifically, between 500 and 750 ms, only transparent nouns showed a significant effect of agreement. Thus, the presence of formal cues to gender also affects RH gender processing but at a later stage than the LH.

Two different explanations could account for this time course difference. One possibility is that only the LH is able to detect gender-related endings through the form-based route and the RH shows effects of the noun transparency manipulation due to interhemispheric communication. Although information can be sent via the corpus callosum with a very short delay (of about 10–15 ms, Hoptman & Davidson, 1994), different sources of evidence would suggest that information is not always fully transferred and callosal transfer can be incomplete (Weissman & Banich, 2000). If this is the case, between 500 and 750 ms, late checking processes could take place, integrating and contrasting information from both hemispheres. After the early detection of formal cues to gender (350–500 ms), the LH could send to the RH a stronger input for transparent nouns than for opaque nouns. This difference would result in a significant interaction during the second time window of RH computation.

However, it has to be noted that, although studies on split-brain patients and healthy participants have shown that RH grammatical abilities are quite limited in comparison to those of the LH (Liu et al., 1999; Gazzaniga & Hillyard, 1971; Gazzaniga et al., 1984) especially in the morphosyntactic domain (Koenig et al., 1992; Zaidel, 1983), they did not rule out the possibility that the RH is completely unable to carry out sub-lexical analysis (for a review on RH linguistic abilities see Lindell, 2006). An alternative explanation therefore could be that both hemispheres are able to use the form-based route and detect gender-related endings, but the LH is faster than the RH, given its specialisation for sub-lexical analysis (Koenig et al., 1992; Zaidel, 1983). Thus, since the LH is particularly skilled in detecting gender-related endings, it would start to use these formal cues at an early stage (between 350 ms and 500 ms). On the other hand, the RH would detect transparent endings only at around 500 ms, when the processing of gender agreement has already started. If this is the case, our ERP results would suggest that the two hemispheres differ also in the way they use the form-based route. While the LH starts to use the lexical and form-based routes at the same stage (at around 350 ms), the RH may start to activate the lexical route between 350 and 500 ms (in order to compute agreement dependencies). Only after 500 ms it may take advantage of the information conveyed by the word form. During this second stage, gender information of the nouns (opaque and transparent) has already been retrieved and formal cues available may be used in late checking mechanisms of agreement processing (Bates et al. 1996), leading to a significant interaction between transparency and agreement in the second time window.

The present results suggest that, when the system needs to recover gender information, different routes can be used depending on the availability of reliable gender cues (e.g., gender-related noun endings). As a consequence, it is possible that the use of the two routes differs across languages depending on how often distributional gender cues are provided. Romance languages usually show a strong gender-to-ending consistency and, thus, they could widely take advantage of the form-based route. In Germanic languages this correspondence is usually less clear. In this case, the lexical route would be more relevant for gender access. Although no study has directly investigated this specific issue, available behavioural and ERP results on gender processing seem to show qualitative differences between these two groups of languages. Specifically, studies using a picture–word interference paradigm led to different results between Romance and Germanic languages (Schiller, 2013). In this paradigm, a target picture was presented together with a distractor word that shared the same grammatical gender or not. Participants were required to name the target using a noun phrase (e.g. determiner–adjective–noun). When the target and the distractor had a different gender, the selection of the gender feature of the target was delayed as compared to when they shared the same gender. While this gender congruency effect is a stable result in Germanic languages, research has failed to replicate this effect in Romance languages (Schiller, 2013 for an overview). Similarly, ERP studies on gender agreement processing have shown variable results depending on the type of language. Specifically, the LAN effect observed with gender agreement violations seems to be more consistent in Romance languages (i.e., Spanish, Italian) than in Germanic ones (i.e., German, Dutch; for a discussion see Molinaro et al., 2011). Further investigations would be helpful to establish whether the different availability of distributional cues could account for these cross-linguistic differences in gender processing.

To conclude, the present experiment provides behavioural and ERP evidence for the existence of two routes to grammatical gender. Whereas the lexical route recovers gender as an abstract feature stored in the lexicon, a form-based route takes advantage of formal cues to access gender. The two hemispheres seem to use these formal cues to gender at different stages of processing. While the LH activates the form-based route from 350 ms, the RH uses the form-based information only at a later stage (after 500 ms).

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2014.08.016.

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